Low Energy RHIC electron Cooling (LEReC):

LEReC Status

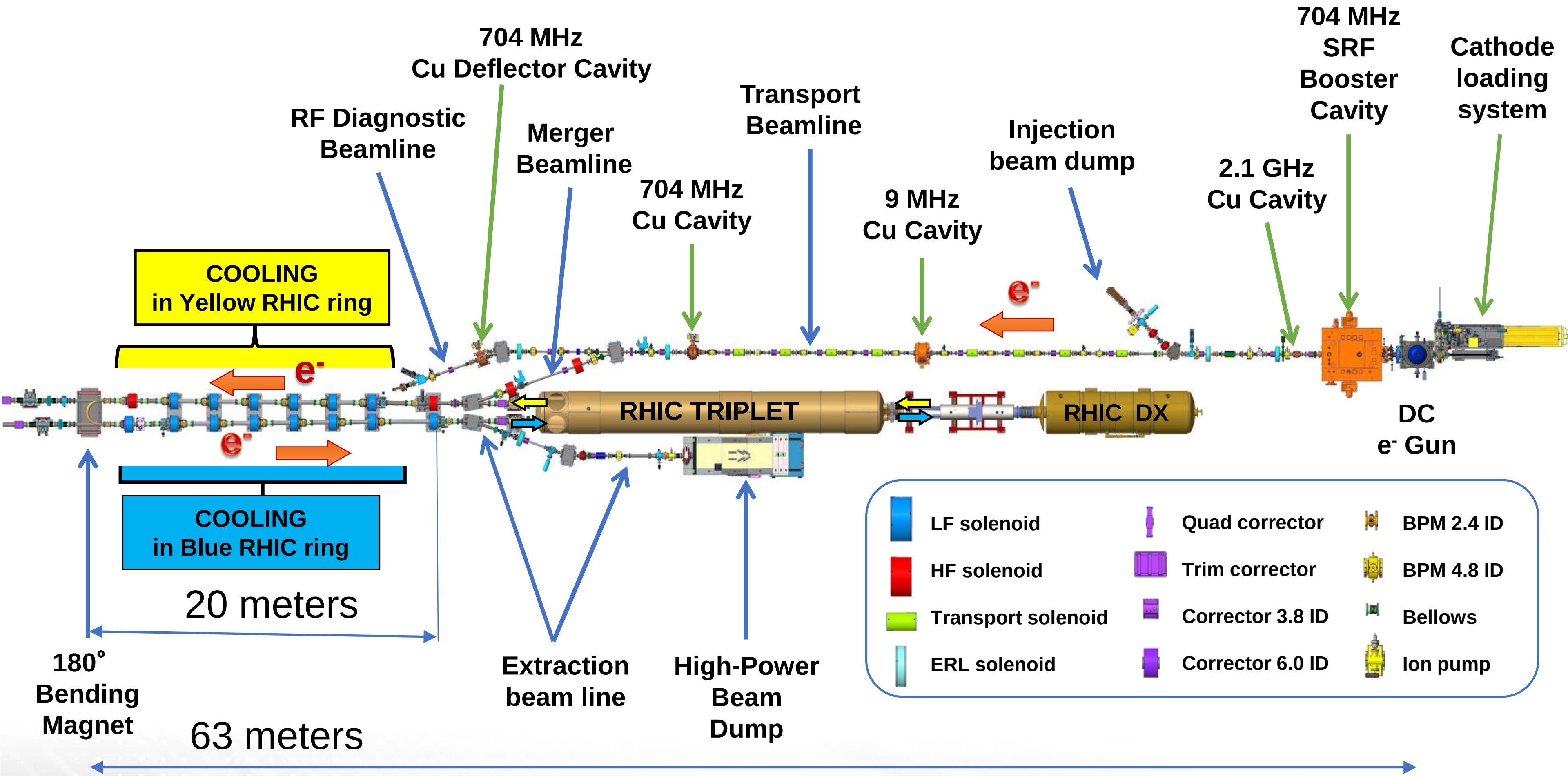
Alexei Fedotov
on behalf of LEReC team

C-AD MAC
December 1- 4, 2020

Outline

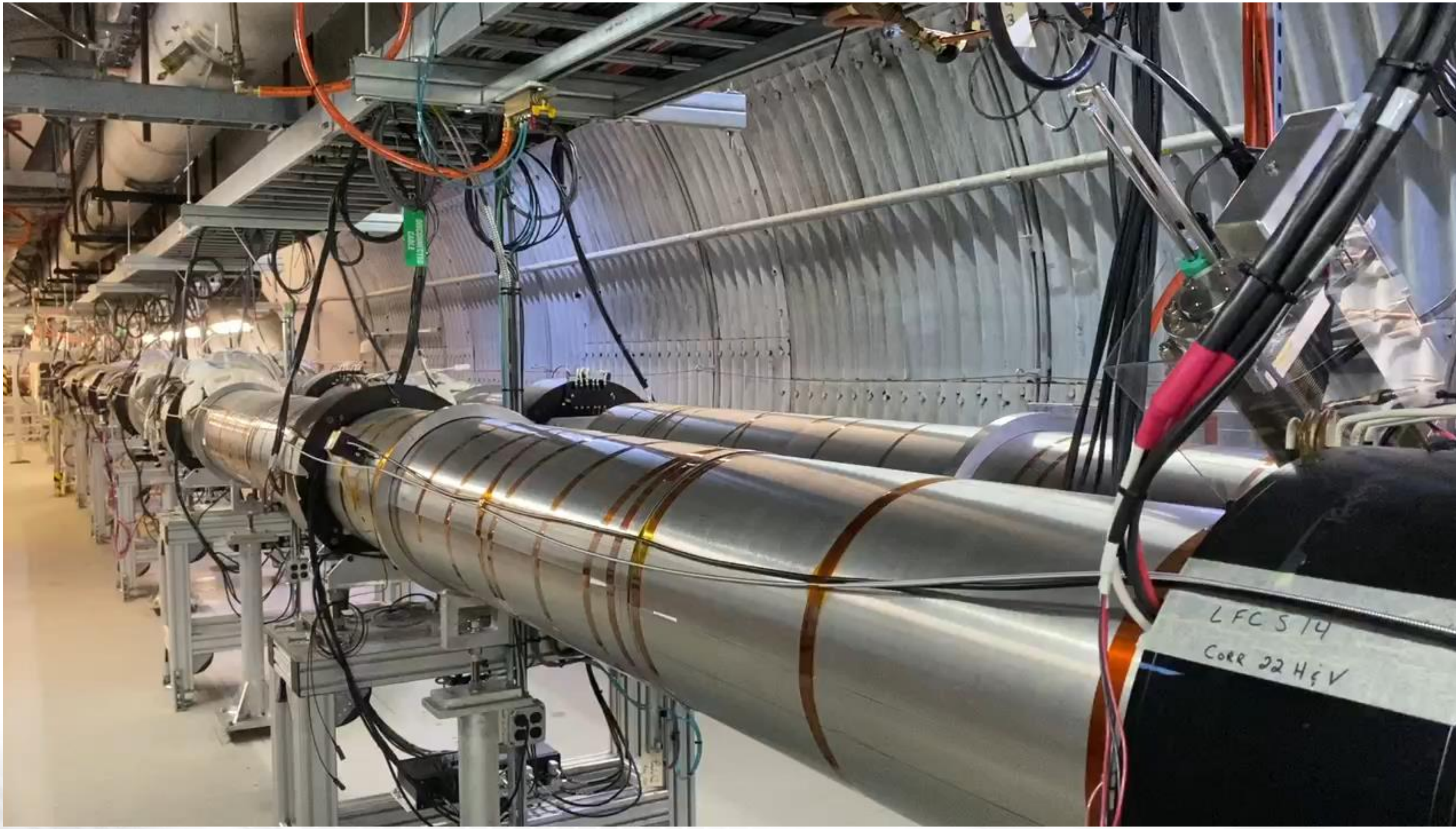
- Operational experience
- Electron cooling in a collider and limitations at low-energy
- 1.4 GHz RF cavity upgrade
- Expected performance with 1.4 GHz cavity; e-beam dynamics, simulations of heating and cooling
- Future plans: cooling and accelerator R&D

LEReC – world's first electron cooler based on rf-accelerated electron bunches employing high-current electron accelerator (as such, a prototype of high-energy cooler)



* NOT to scale

Cooling sections (20 meters each) in Yellow and Blue RHIC rings



LEReC summary for 2020

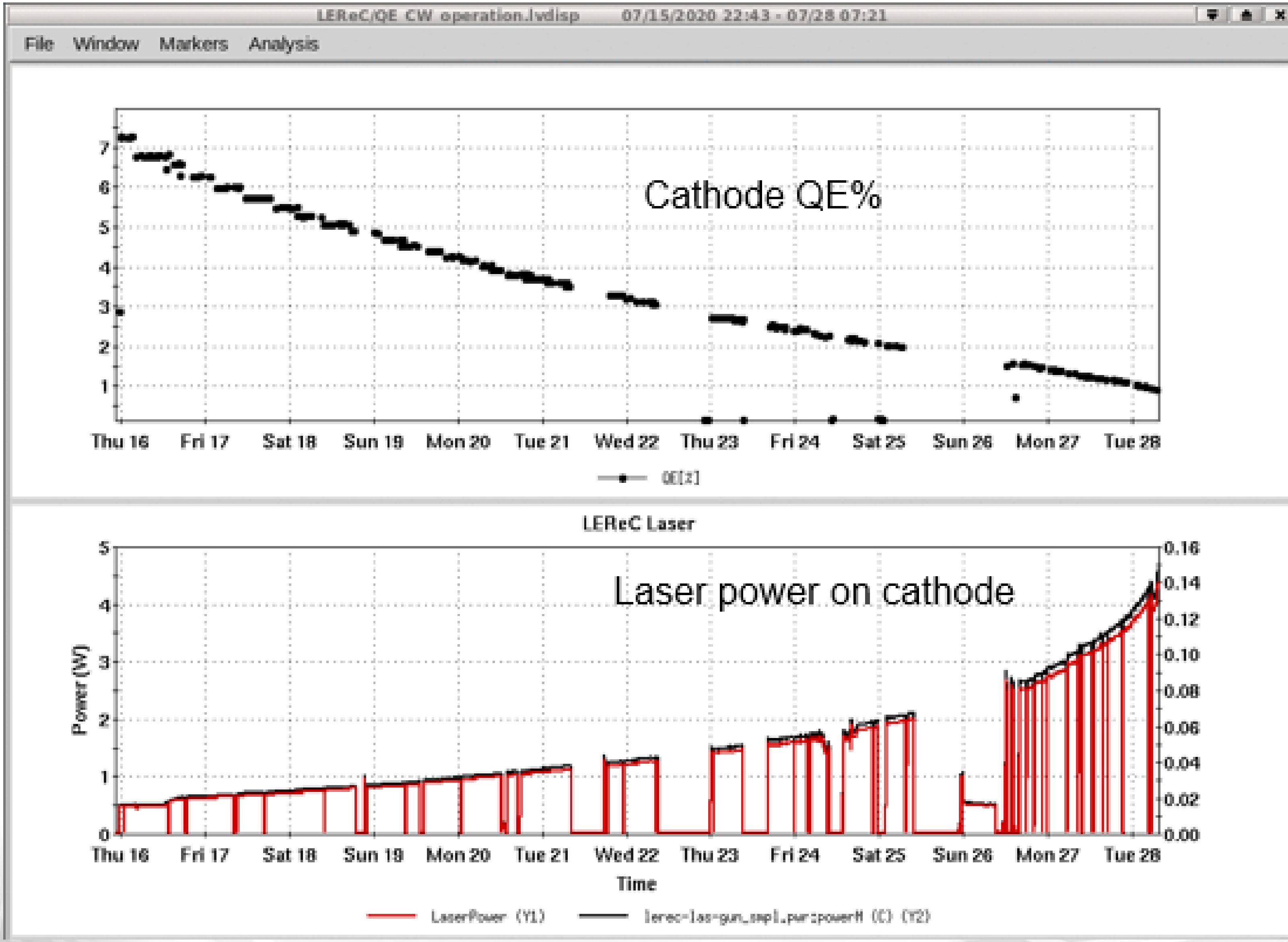
- Cooling was commissioned and optimized using 2MeV electron beam for Physics operation with Au ions at 4.6GeV/nucleon
- Electron-ion beam alignment in cooling sections was improved by implementing the channel switching scheme for BPMs electronics which resulted in improved transverse cooling
- Cooling was made fully operational, including implementation of laser position feedbacks, intensity feedback, energy feedback, automatic cooling section orbit corrections and feedback
- Stable 24/7 running for Physics at 4.6GeV of high-current electron accelerator over many weeks
- Cooling was commissioned using 1.6MeV electron beam for Physics operation at 3.85GeV/nucleon in 2021.

World’s first electron cooling in a collider (cooling of ion beams in collisions and luminosity optimization with cooling) became operational.

LEReC operational experience in 2020

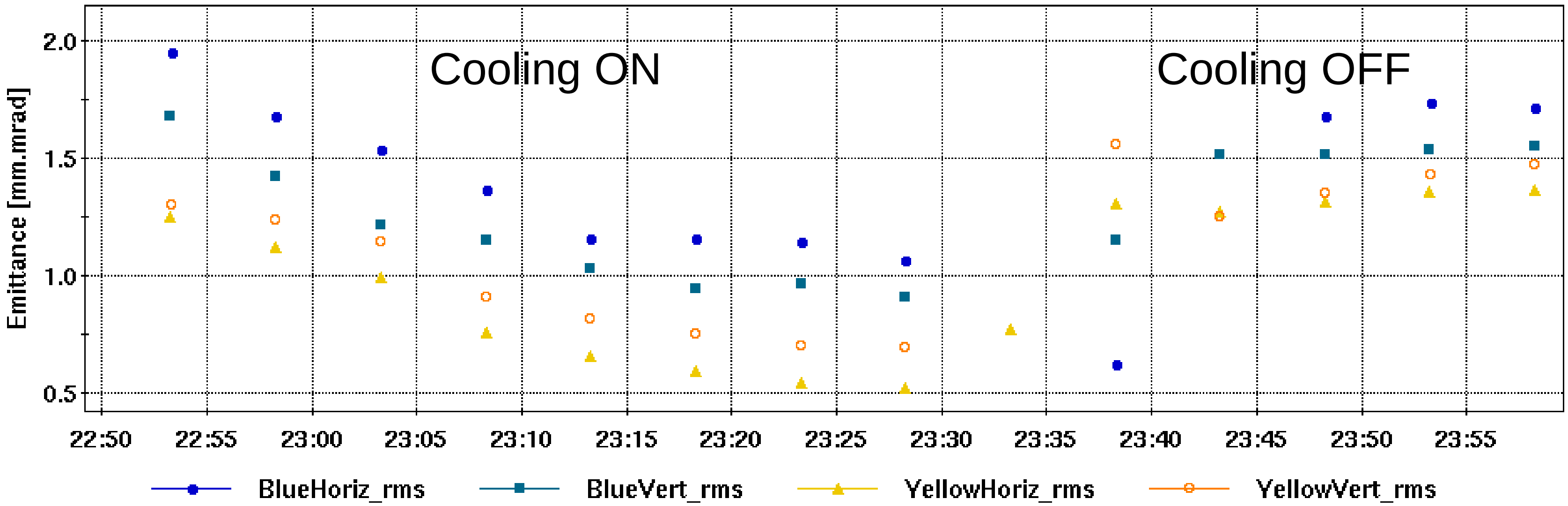
- Overall, stable and reliable operation of all accelerator systems with high-current (15-20mA) electron beam
- Very robust cathodes with high QE (typical initial QE around 8%)
- Most MPS trips during high-current operation were caused by beam losses, BPMs and RF cavities. Typical recovery time was very fast (it takes few minutes to clear MPS and ramp up e-beam current).
- Occasional RF trips due to Power Amplifiers or due to laser beam becoming less stable. SRF cavity required conditioning by the end of the run.
- Very few Gun trips at high-current. Most trips happened when anode ion clearing power supply was down resulting in ion back bombardment. Gun was reconditioned at the end of the run.

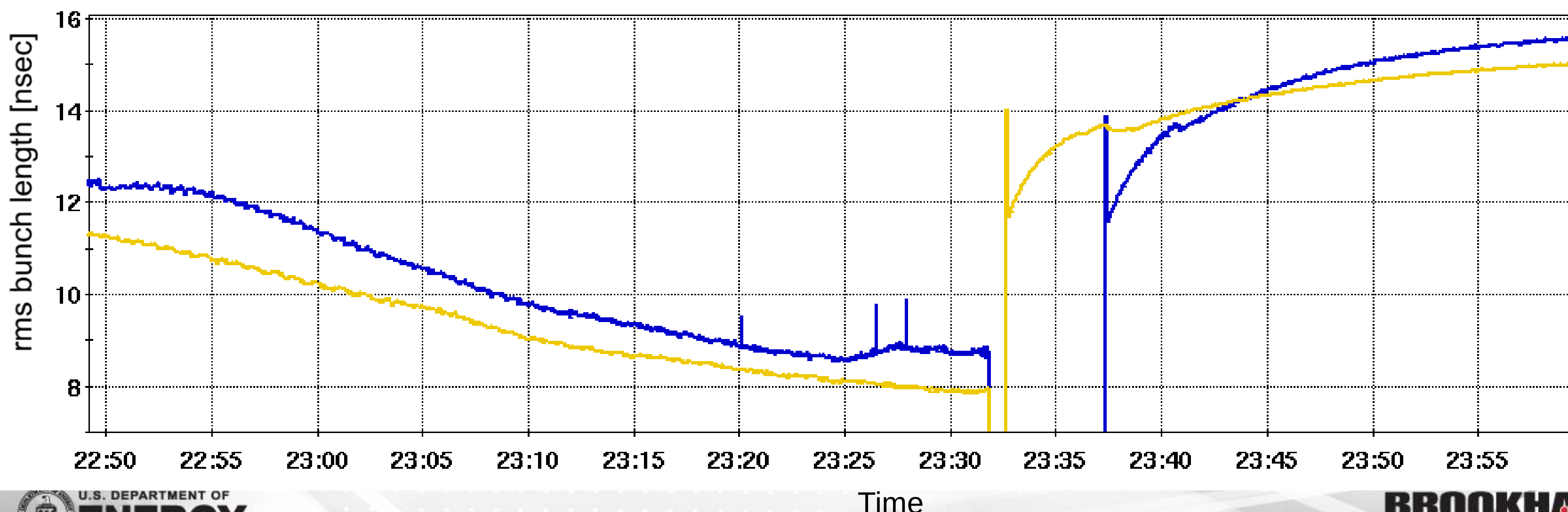
Typical cathode performance



Physics stores (at 4.6 GeV/n) with and without cooling

(rms emittances (top) and bunch length (bottom) of ions in Yellow and Blue RHIC rings)





Cooling in a collider

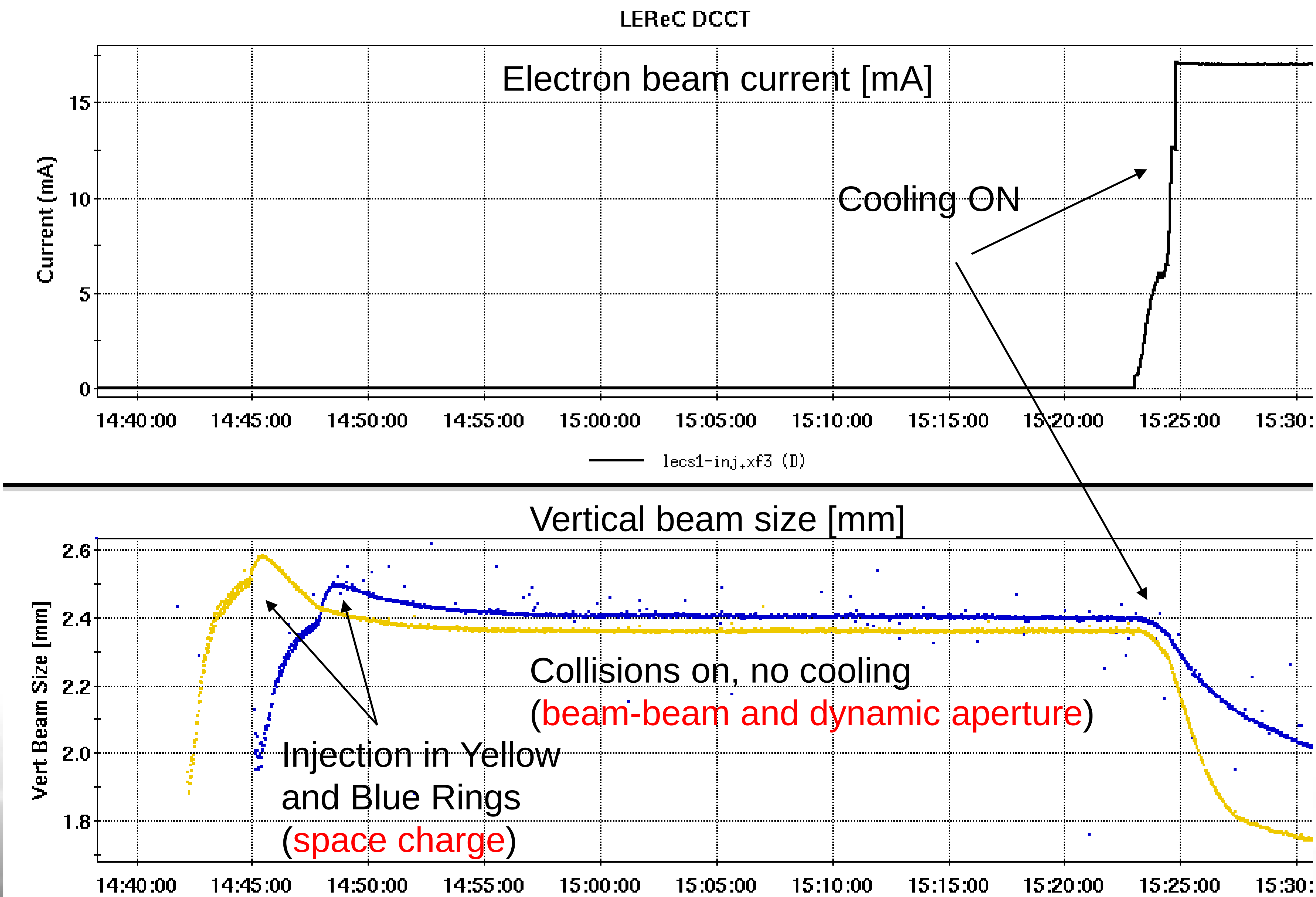
After 6D electron cooling of hadron beams was successfully commissioned in both RHIC rings in 2019, our focus shifted towards operational aspects of cooling of full RHIC stores with ion bunches in collisions.

Application of electron cooling technique directly at collision energy of hadron beams brings several challenges, such as:

- Control of ion beam distribution, not to overcool beam core (especially when ion beam space charge is significant)
- Interplay of space-charge and beam-beam in hadrons
- Effects on hadron beam from electrons (“heating”)
- Ion beam lifetime with cooling (as a result of many effects)
- Optimization between cooling process and luminosity improvement

The final optimization was performed during operation for physics by choosing parameters which result in largest luminosity gains (not necessarily higher electron beam current or stronger cooling)

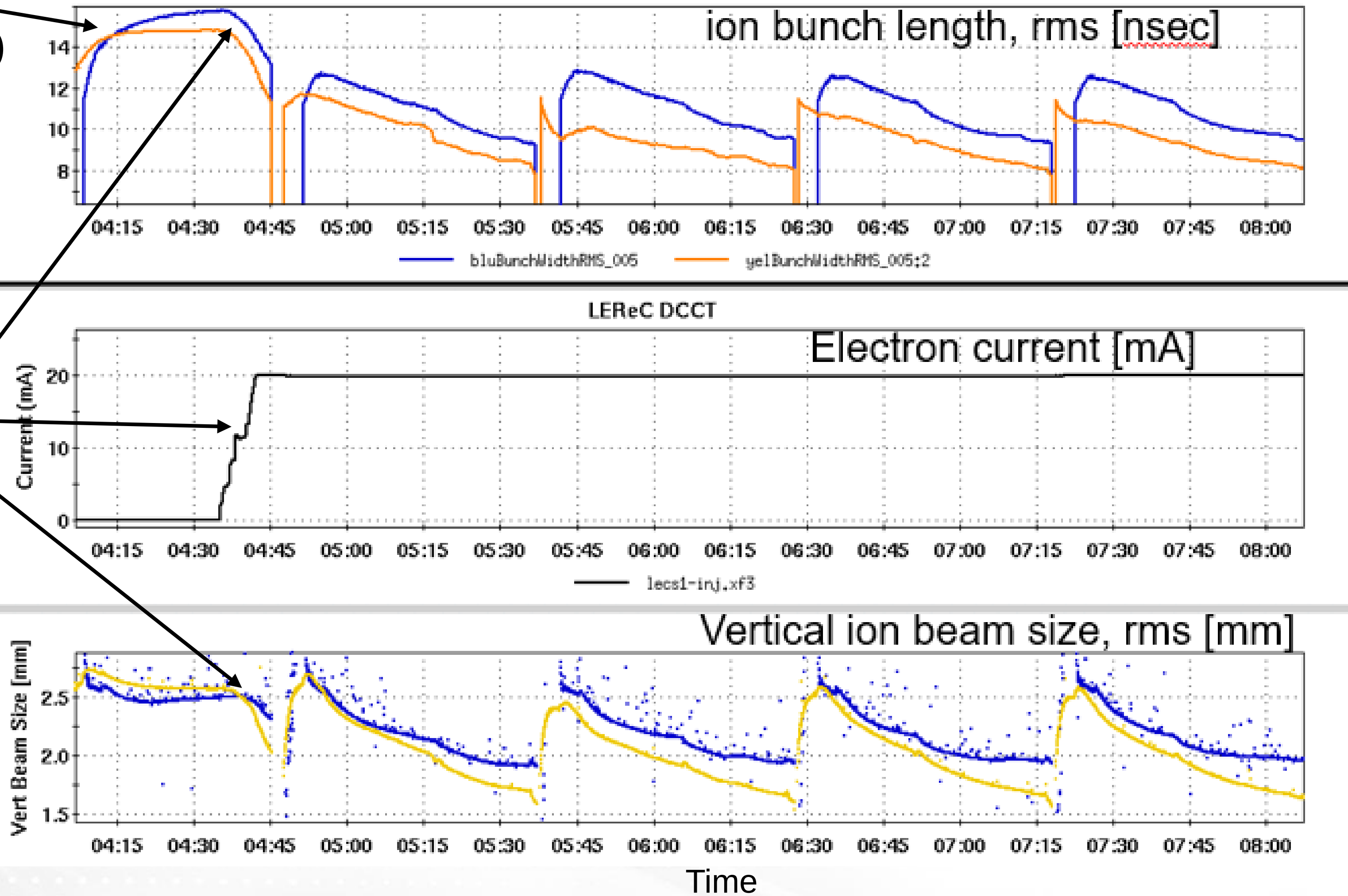
Ion beam limitations at low energies with collisions (space charge, dynamic and physical aperture, beam-beam)



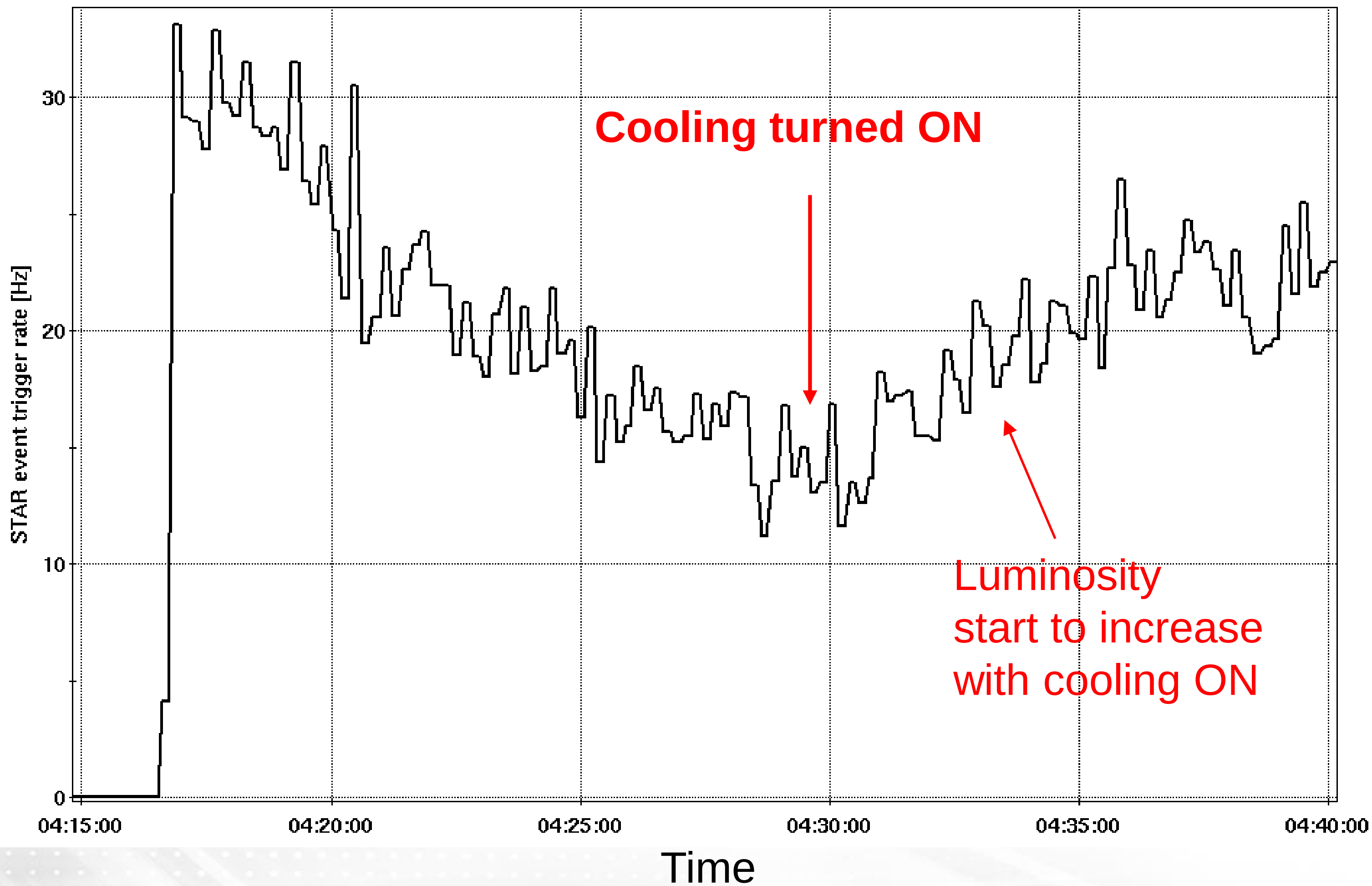
Cooling of hadron beams in Yellow and Blue RHIC rings during physics stores (Au ions at 4.6 GeV/n, 2MeV electrons)

Cooling is off (during first store)

Cooling starts when electron current is being ramped up.



Physics store with electron beam (cooling) restored later in the store

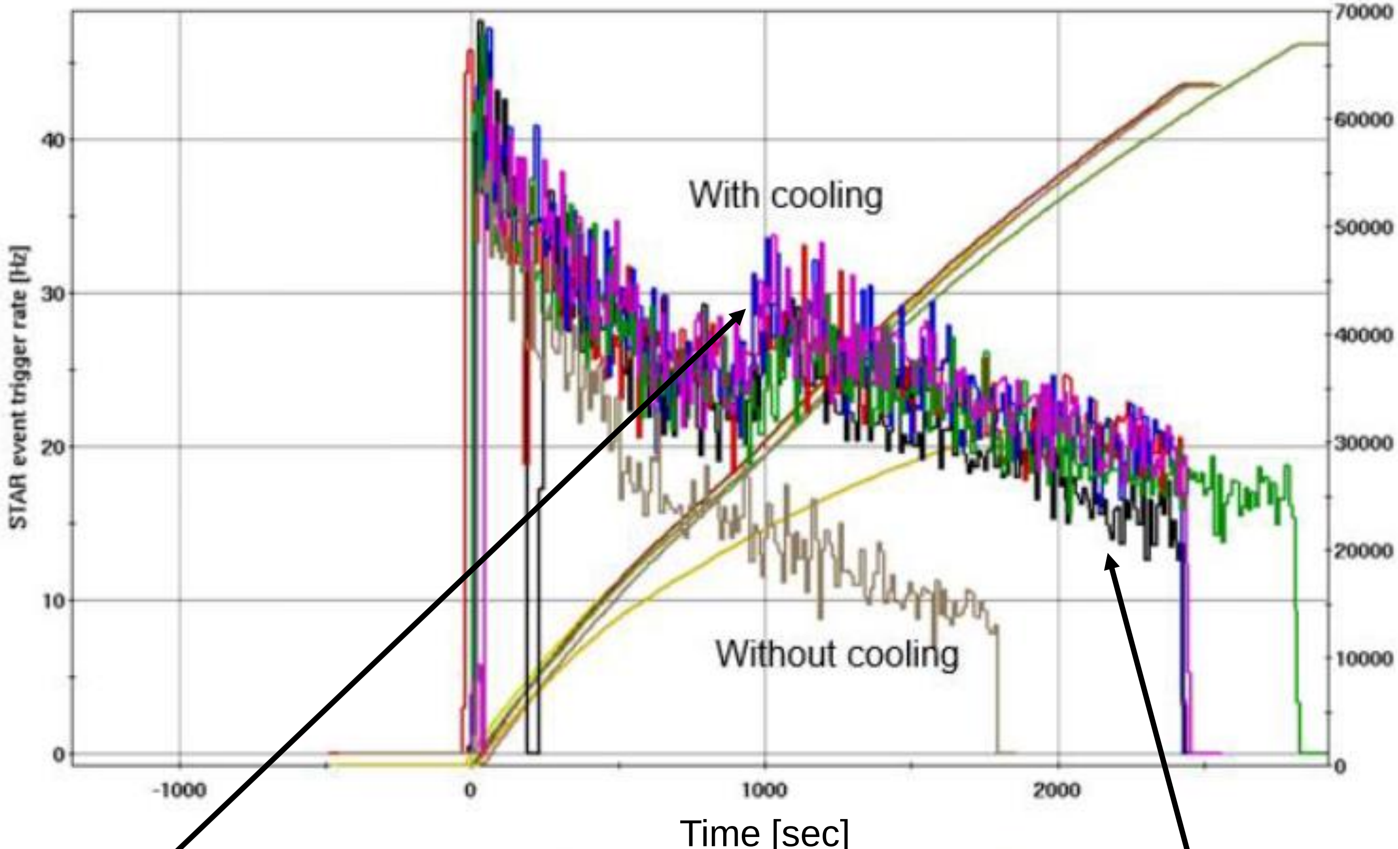


Cooling optimization for luminosity

Luminosity optimization with cooling is ongoing but the following was already successfully tried during physics operation with Au ions at 4.6 GeV/nucleon:

- Finding optimum angular spread of electrons in cooling sections to provide sufficient cooling
- Optimization of electron and ion beam sizes in the cooling sections
- Finding optimum electron current to reduce heating effects on ion beam and still provide sufficient cooling
- Longer stores with cooling
- With cooling counteracting longitudinal IBS and preventing debunching from the RF bucket, ions RF voltage was reduced resulting in smaller momentum spread of ions and improving ion lifetime
- Once good transverse cooling was established dynamic squeeze of ion beta-function at the collision point was implemented

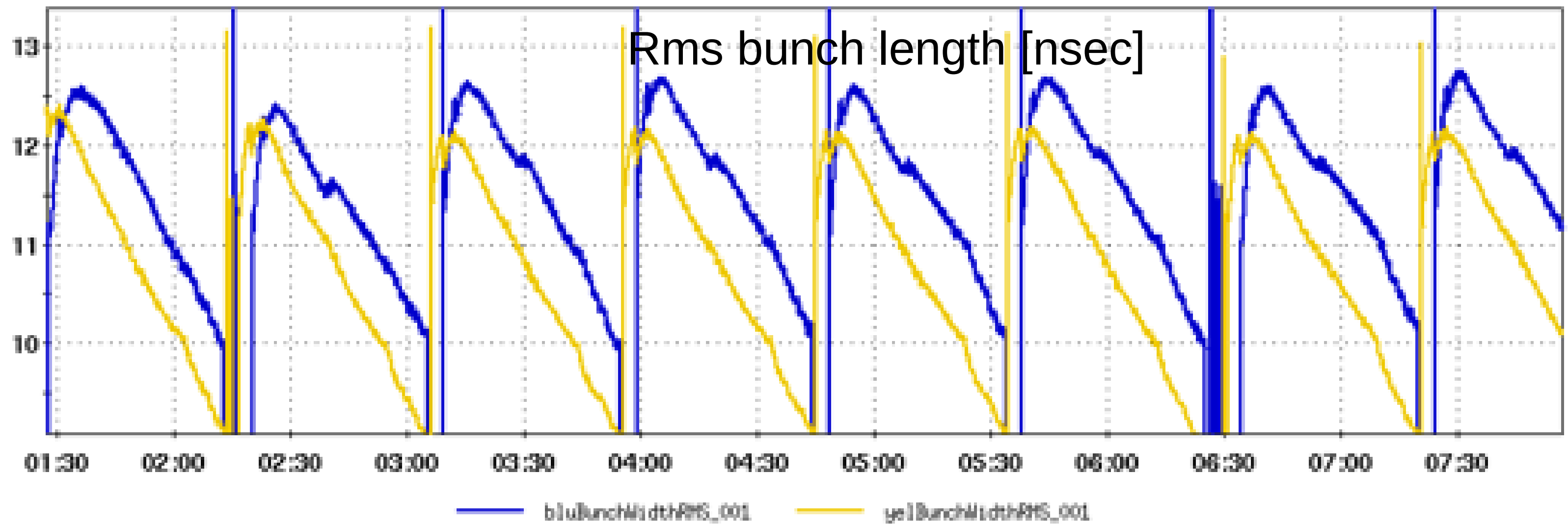
Several physics stores at 4.6 GeV/nucleon with cooling (2 MeV electrons) (vertical axis: events rate [Hz] within +/-0.7m (left); store integrals (right))

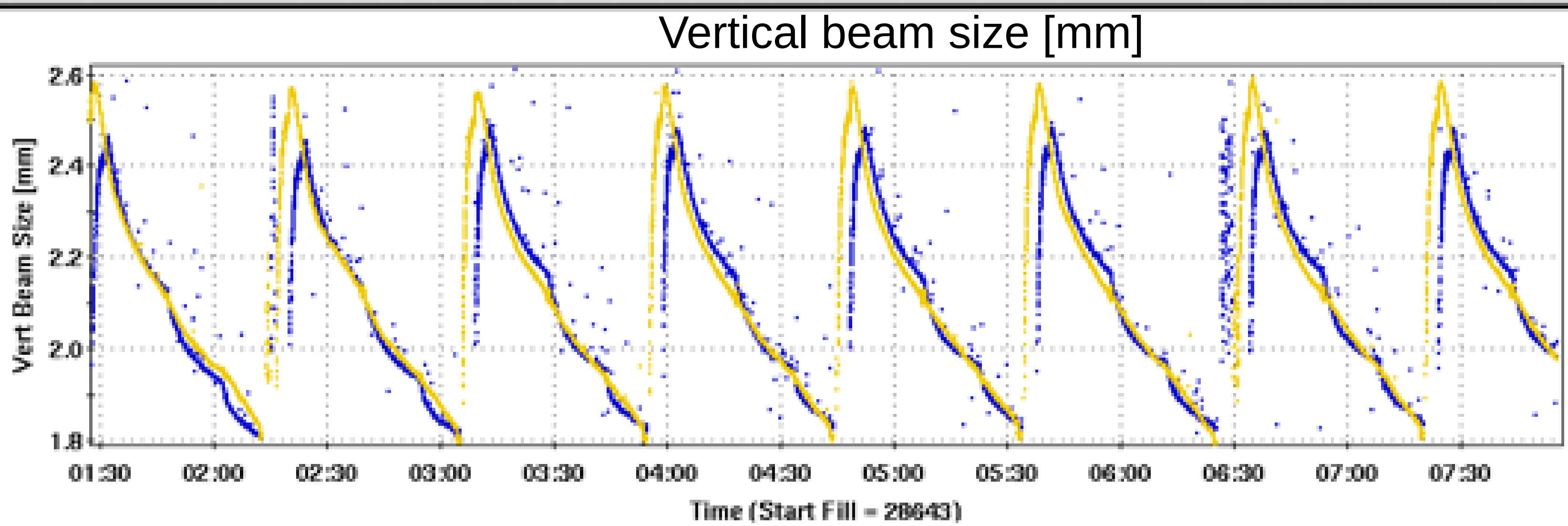


Dynamic squeeze of beta-function at collision point, while transverse beam sizes of ion beams are being cooled

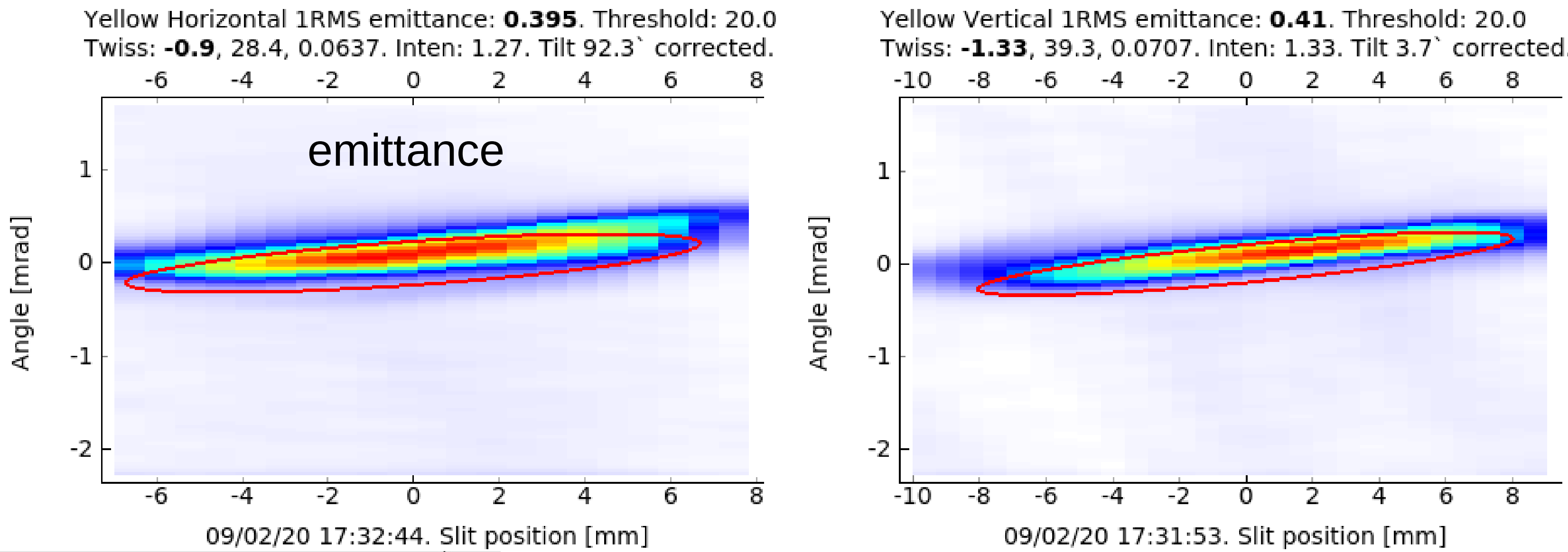
Longer stores with cooling

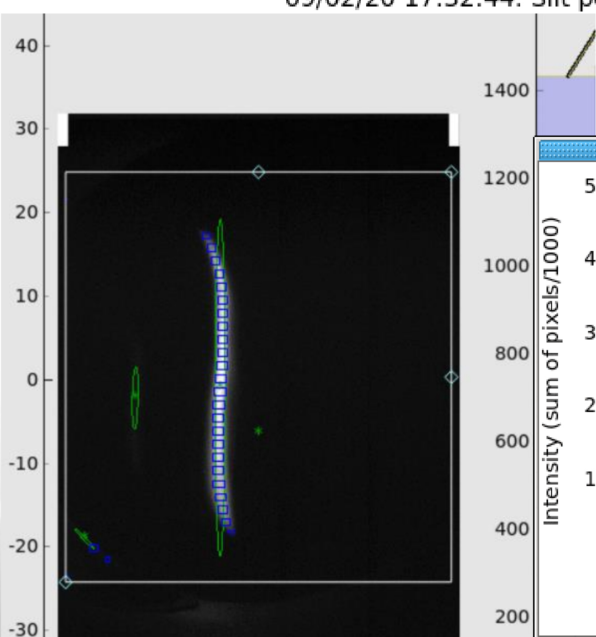
Typical cooling performance (August 26, 2020), 2 MeV electrons, Au ions at 4.6GeV/n



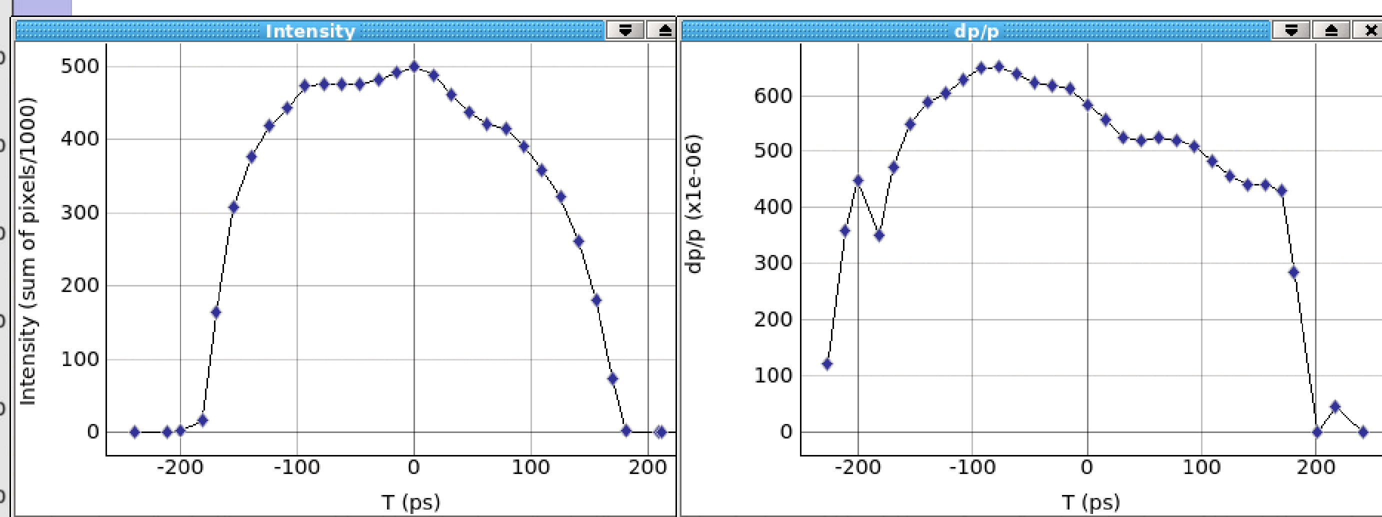


Measured electron beam quality at 1.6MeV, for cooling of Au ions at 3.85GeV/n (September 2020)



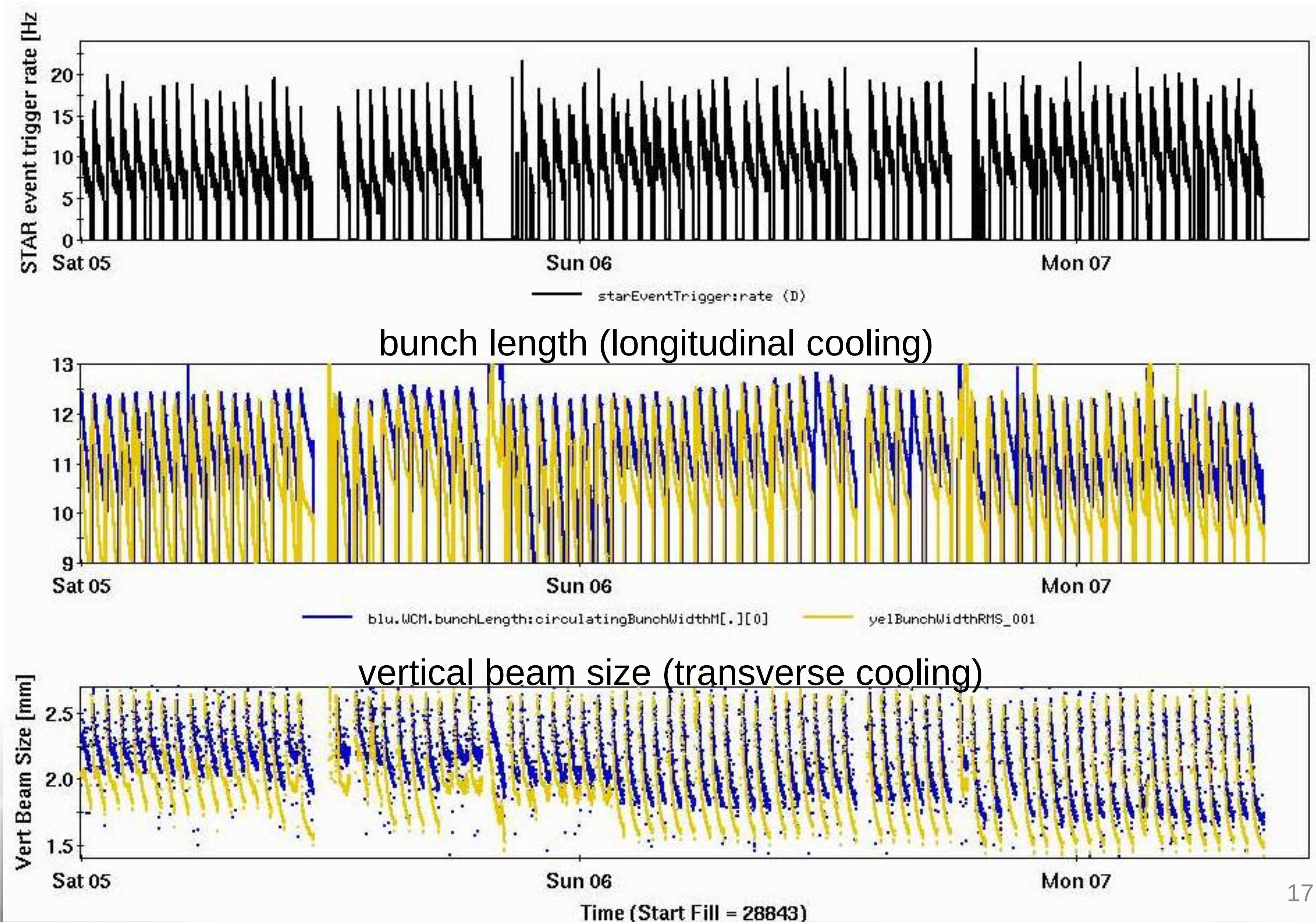


Energy spread



Baseline run with cooling at 3.85 GeV/n (September 5-7)

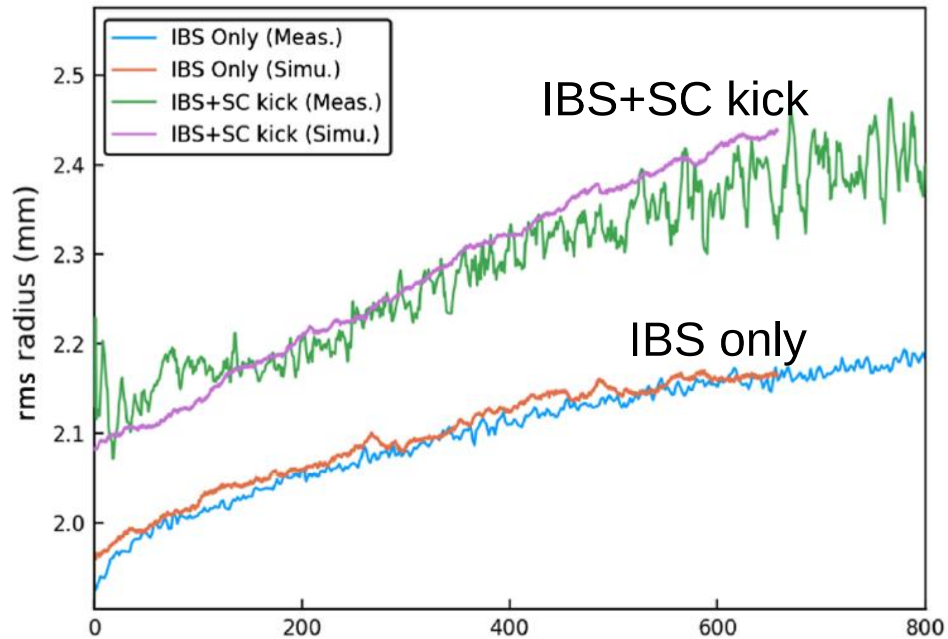
Stable and efficient operation of LEReC (1.6MeV electrons)



Cooling limitations and upgrades

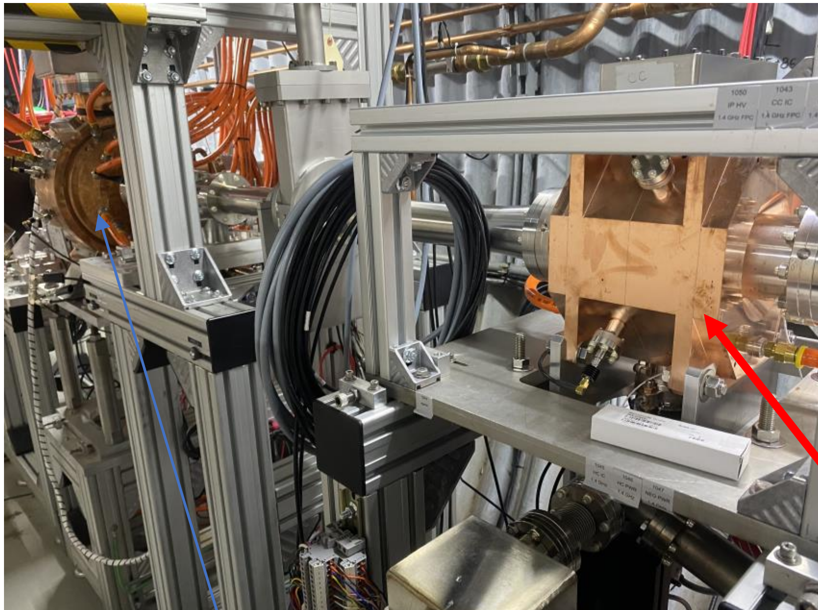
- Cooling is designed to counteract beam growth due the IBS
- For LEReC with bunched electron beam it was found that space-charge kicks from electron on ions can result in additional emittance growth of ions, we refer to this effect as "heating".
- Due to space-charge scaling this heating depends on electron beam peak current and becomes stronger at low energy.
- Such heating effect can be reduced by operation with longer electron bunches.
- To produce longer electron bunches with comparable or smaller energy spread, second harmonic linearizing RF cavity (1.4GHz) was added

Simulations vs measurements



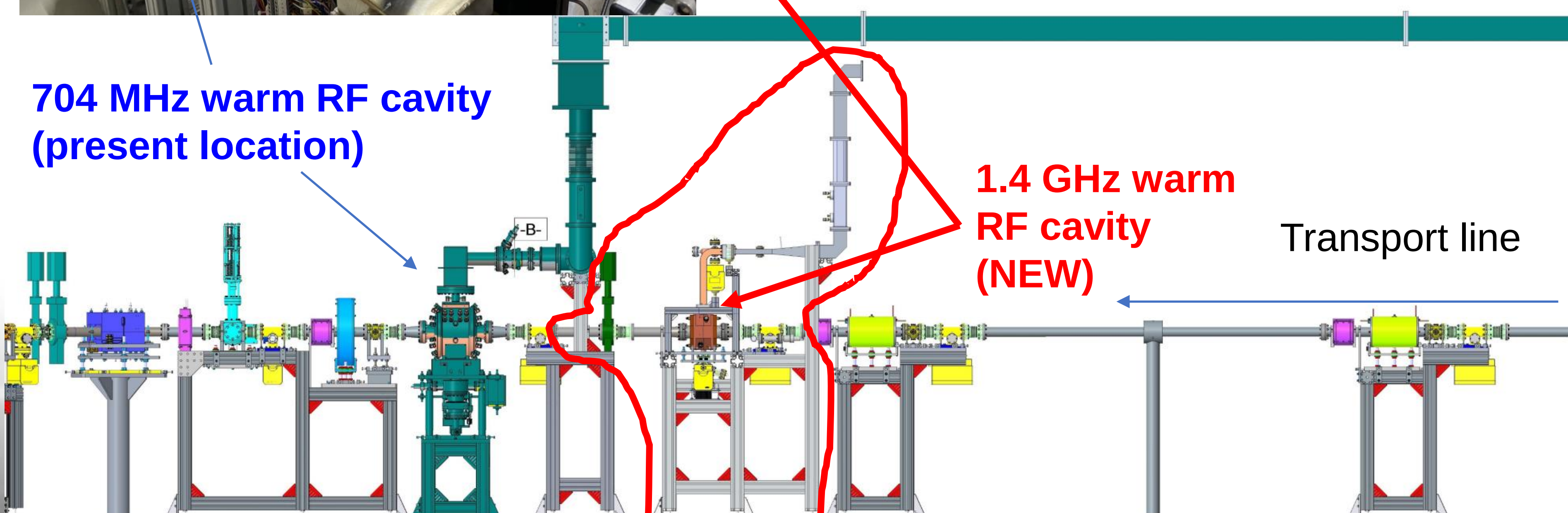
*H. Zhao et al., Phys. Rev. Accel. Beams **23**, 074201 (2020)*

2021 upgrade: New 1.4GHz (second harmonic) RF cavity



New 1.4GHz cavity is installed to allow for operation with longer electron bunches for the lowest energy of operation.

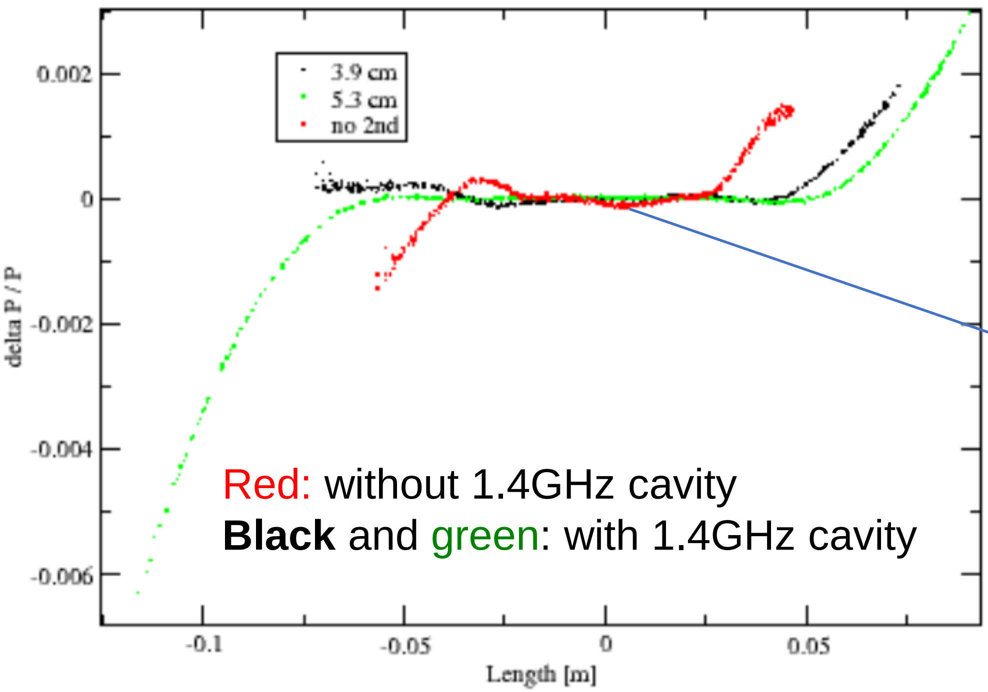
This cavity is installed next to the 704MHz de-chirping cavity and linearizes the wave form used to remove the energy chirp.



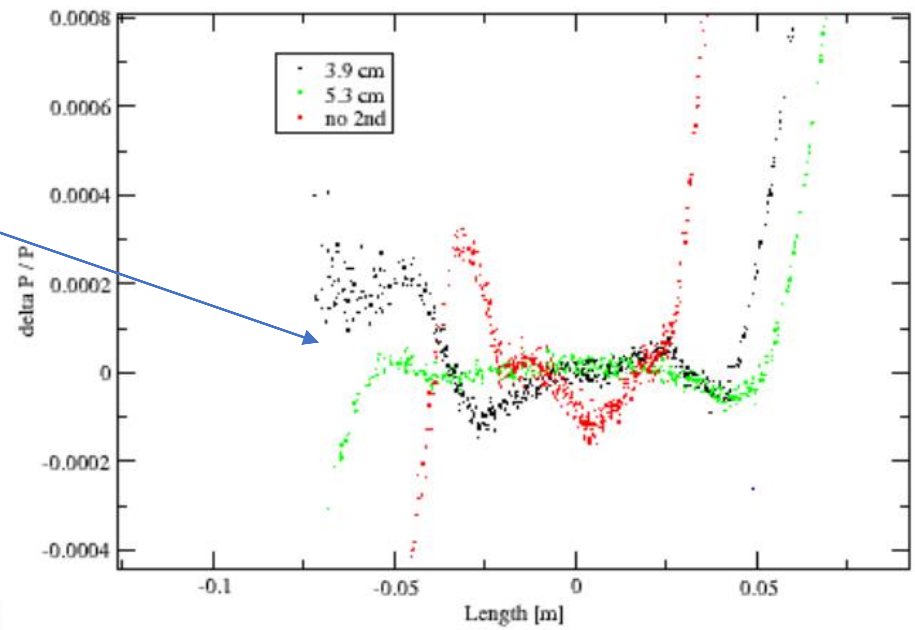
Expected longitudinal performance with 1.4GHz cavity

- Increase in electron bunch length by preserving the same sliced energy spread
- Longer bunch length should result in reduced “heating” effect from electrons on ions (“heating” is due to the space-charge effect from electrons on the ions and is stronger for low energies)

Longitudinal phase space

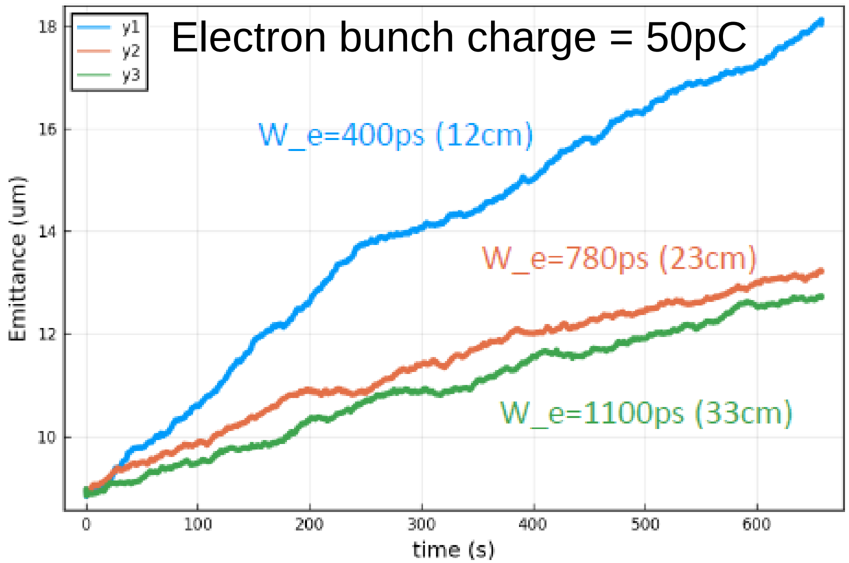


Smaller scale

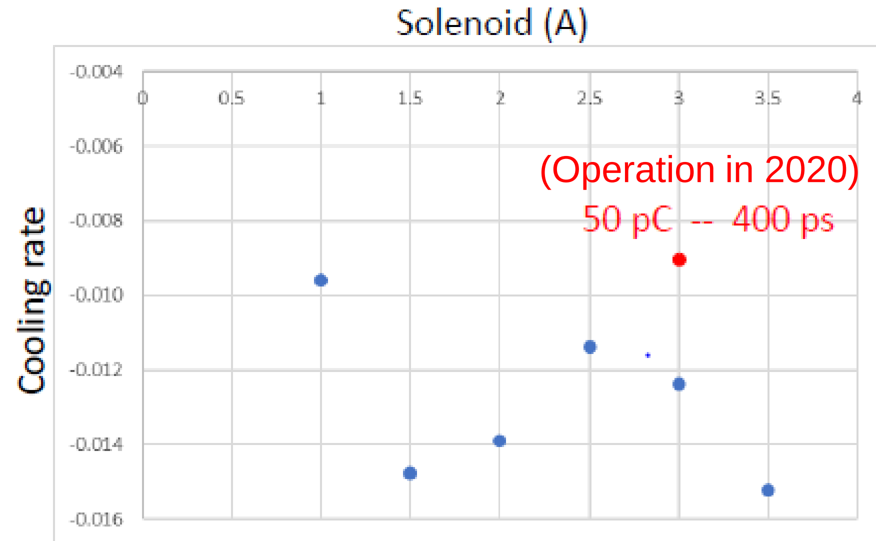


Simulations of heating/cooling and expected performance (for various length of electron bunch)

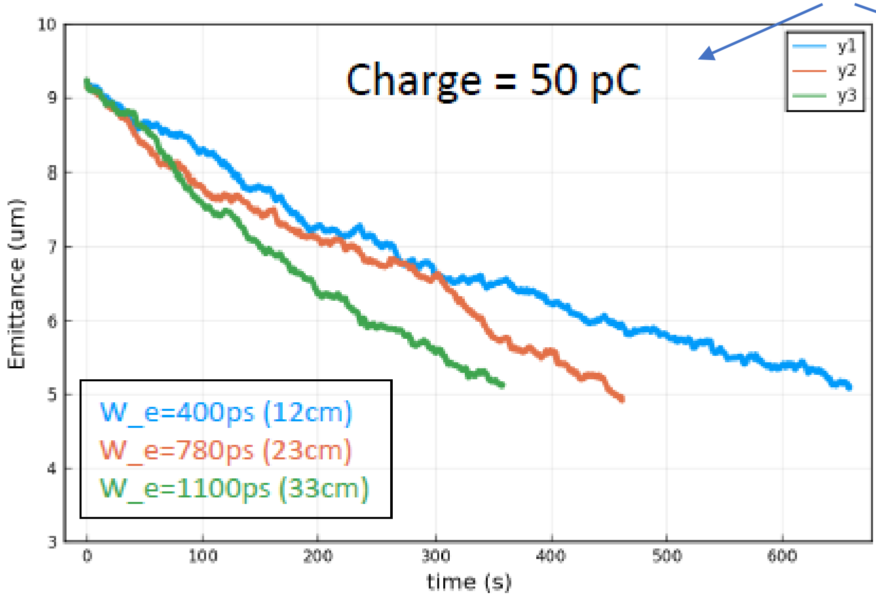
Heating+IBS, No cooling

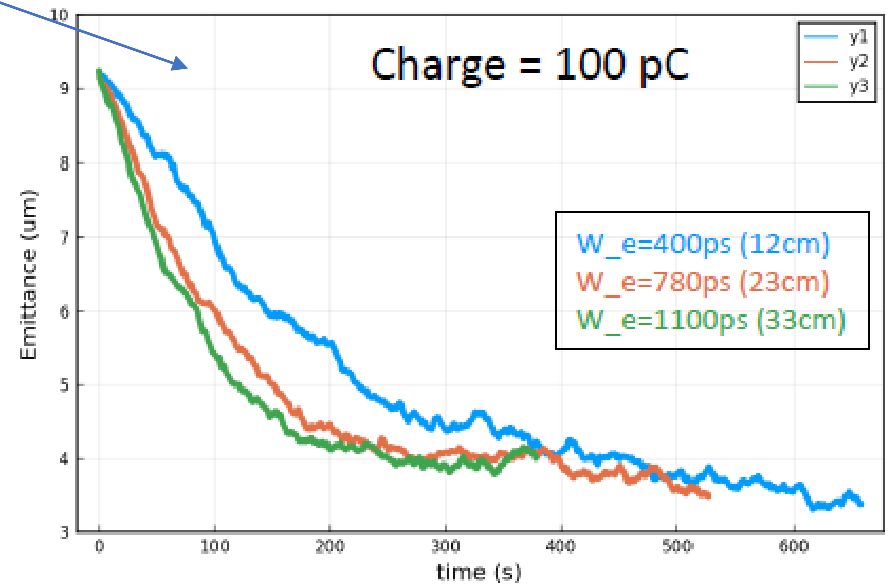


Cooling section optics optimization



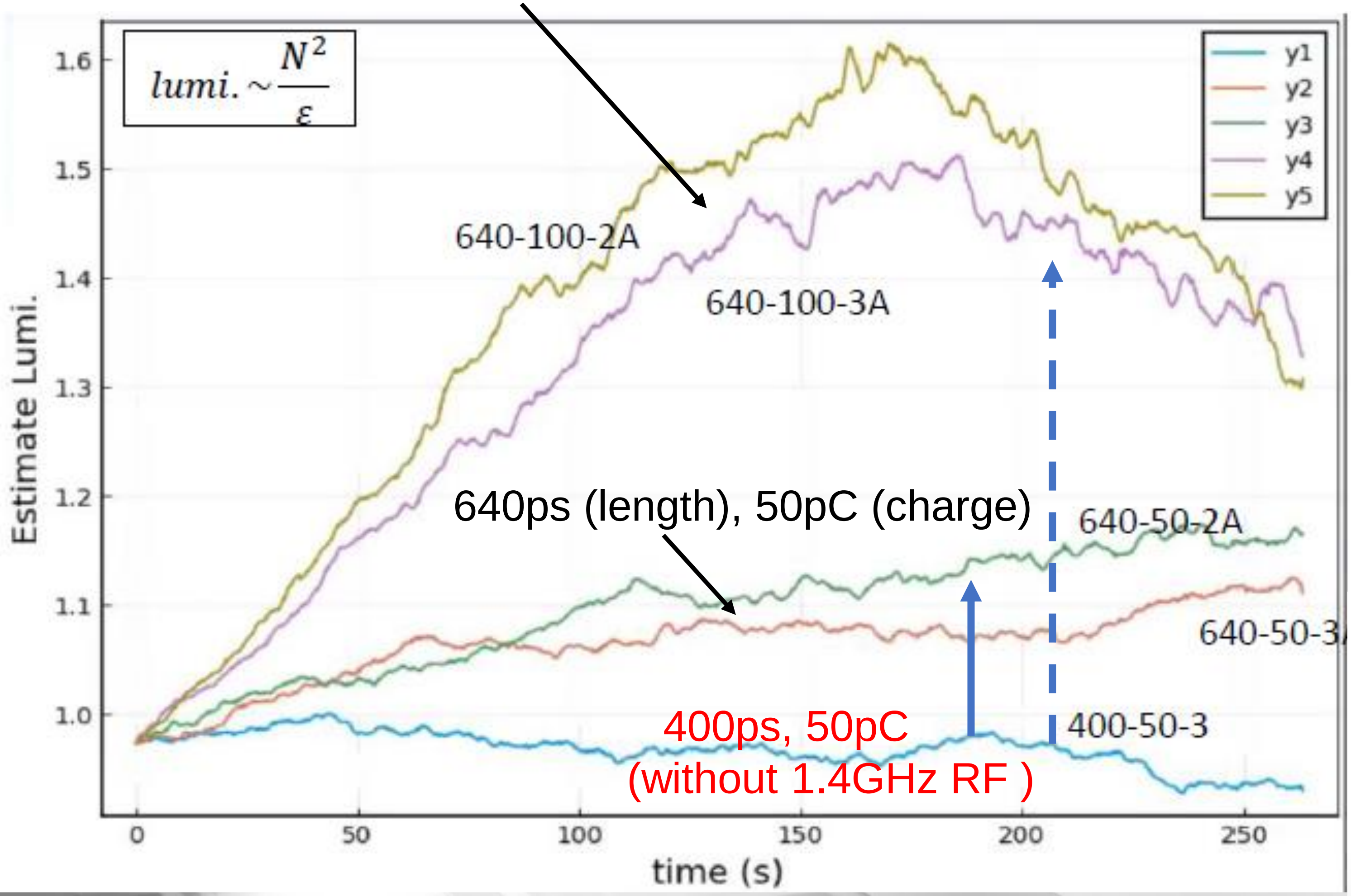
With cooling

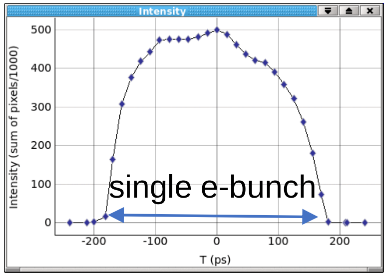


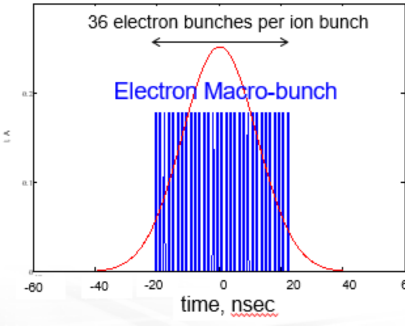


Simulations of potential luminosity improvement with longer electron bunches

640ps (e-bunch full length),
100pC (charge per e-bunch, 36 e-bunches per macro-bunch)







LEReC-based R&D: Cooling studies

With the non-magnetized electron cooling fully commissioned, LEReC offers unique opportunity to study cooling topics which could be of great importance for future high-energy electron coolers, including those proposed for the EIC.

- **Effects of coherent angles and misalignments on cooling process itself and ion beam dynamics under cooling**
- **Effects of ion and electron dispersion in the cooling section on cooling rates and redistribution of cooling decrements between the longitudinal and transverse degrees of freedom**
- **Effect of electrons on ion beam lifetime**
- **Other cooling/heating studies**

See S. Seletskiy presentation for details

LEReC-based R&D: Source/accelerator studies

High-current electron sources is important area of research. They are also required for various cooler designs of the EIC. For example, ERL-based electron cooler for pre-cooling at low energy (LEC) requires stable operation with 100-120mA currents, while Strong Hadron Cooler (SHC) ERL presently employing 100mA source of CW electrons.

- **High current studies**:

LEReC Gun is designed to operate with high current. One can go up to about 100mA with a single HVPS inverter, for example. It should be possible to go above 100mA with two inverters in parallel, but this has to be demonstrated (LEReC has several inverters available).

Many other R&D items critical to high-current operations

- **Other LEReC-based accelerator R&D**:

Electron beam dynamics, high-current high-power diagnostics, possibly high-current ERL

See D. Kayran presentation for details

LEReC plans for 2021

Nov. - Dec. 2020:	Commissioning of new 1.4GHz RF cavity and related systems
January 2021:	Once SRF booster is at 2K, SRF tests and conditioning
January 2021:	Commissioning of electron accelerator with new 1.4GHz RF cavity
February 2021:	Cooling commissioning and optimization with 1.4GHz RF cavity and longer bunches
February 2021:	Physics run with cooling at 3.85GeV.
February – June 2021:	Cooling studies and R&D for high-energy cooling (as APEX)

Summary

- World’s first electron cooling in a collider was successfully commissioned and became fully operational during 2020 RHIC Physics run with Au ions at 4.6GeV.
- Stable and reliable high-current accelerator operation and robust cooling performance during many weeks of Physics running
- Cooling was commissioned for Physics operation at 3.85GeV.
- New 1.4 GHz RF cavity and supporting systems are installed for operation in 2021
- LEReC is the only electron cooler which uses non-magnetized electron bunches produced with rf-acceleration. As such, it offers unique opportunity to study various effects relevant to high-energy cooling. We plan to do such experimental studies in 2021 and possibly beyond.
- Being high-current high-brightness electron accelerator LEReC also offers a possibility for extensive high-current accelerator R&D

Recent LEReC peer-review publications

- A. Fedotov et al., ” Experimental demonstration of hadron beam cooling using radio-frequency accelerated electron bunches”, Physical Review Letters 124, 084801 (2020).
- D. Kayran et al., ” High-brightness electron beams for linac-based bunched beam electron cooling”, Phys. Rev. Accel. Beams 23, 021003 (2020).
- S. Seletskiy et al., ” Accurate setting of electron energy for demonstration of first hadron beam cooling with rf-accelerated electron bunches”, Phys. Rev. Accel. Beams 21, 111004 (2019).
- X. Gu et al., ”Stable operation of a high-voltage high-current dc photoemission gun for the bunched beam electron cooler in RHIC”, Phys. Rev. Accel. Beams 23, 013401 (2020).
- H. Zhao et al., ”Cooling simulation and experimental benchmarking for an rf-based electron cooler”, Phys. Rev. Accel. Beams 23, 074201 (2020).
- S. Seletskiy et al., ”Obtaining transverse cooling with non-magnetized electron beam”, Phys. Rev. Accel. Beams 23, 110101 (2020).